Patient geometry-driven information retrieval for IMRT treatment plan quality control

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Purpose: Intensity modulated radiation therapy (IMRT) treatment plan quality depends on the planner's level of experience and the amount of time the planner invests in developing the plan. Planners often unwittingly accept plans when further sparing of the organs at risk (OARs) is possible. The authors propose a method of IMRT treatment plan quality control that helps planners to evaluate the doses of the OARs upon completion of a new plan.
Methods: It is achieved by comparing the geometric configurations of the OARs and targets of a new patient with those of prior patients, whose plans are maintained in a database. They introduce the concept of a shape relationship descriptor and, specifically, the overlap volume histogram (OVH) to describe the spatial configuration of an OAR with respect to a target. The OVH provides a way to infer the likely DVHs of the OARs by comparing the relative spatial configurations between patients. A database of prior patients is built to serve as an external reference. At the conclusion of a new plan, planners search through the database and identify related patients by comparing the OAR-target geometric relationships of the new patient with those of prior patients. The treatment plans of these related patients are retrieved from the database and guide planners in determining whether lower doses delivered to the OARs in the new plan are feasible.
Results: Preliminary evaluation is promising. In this evaluation, they applied the analysis to the parotid DVHs of 32 prior head-and-neck patients, whose plans are maintained in a database. Each parotid was queried against the other 63 parotids to determine whether a lower dose was possible. The 17 parotids that promised the greatest reduction in D_{50} (DVH dose at 50% volume) were flagged. These 17 parotids came from 13 patients. The method also indicated that the doses of the other nine parotids of the 13 patients could not be reduced, so they were included in the replanning process as controls. Replanning with an effort to reduce D_{50} was conducted on these 26 parotids. After replanning, the average reductions for D_{50} of the 17 flagged parotids and nine unflagged parotids were 6.6 and 1.9 Gy, respectively. These results demonstrate that the quality control method has accurately identified not only the parotids that require dose reductions but also those for which dose reductions are marginal. Originally, 11 of out the 17 flagged parotids did not meet the Radiation Therapy Oncology Group sparing goal of $V(30\ \mathrm{Gy}) < 50\%$. Replanning reduced them to three. Additionally, PTV coverage and OAR sparing of the original plans were compared to those of the replans by using pairwise Wilcoxon p test. The statistical comparisons show that replanning compromised neither PTV coverage nor OAR sparing.
Conclusions: This method provides an effective quality control mechanism for evaluating the DVHs of the OARs. Adoption of such a method will advance the quality of current IMRT planning, providing better treatment plan consistency. [DOI: 10.1118/1.3253464]

Key words: IMRT, shape relationship descriptor, database, quality control, OVH

I. INTRODUCTION

In the early days of the development of intensity modulated radiation therapy (IMRT), the ultimate goal was to automate the treatment planning process while achieving an optimal balance between target coverage and normal tissue sparing.[1,2] However, now over a decade later, IMRT planning remains a time-consuming process of trial-and-error.[3] Planners manually tweak dose volume histogram (DVH) objectives, repeatedly optimizing the treatment plan until it is clinically acceptable. As organs at risk (OARs) increase in number, the process becomes combinatorially complex. For example, there are over 13 OARs and multiple PTVs for the head-and-neck. Thus, plan quality heavily relies on the time that planners can spend. As a result, planners often unwittingly accept plans when further sparing of the OARs is possible.

The underlying difficulty is that a way of mathematically defining the DVH objectives that accounts for the trade-offs between target coverage and normal tissue sparing has yet to be developed. Much of this inability is due to the variability of the anatomical structures between patients, i.e., the geometric relationship between each target and OAR.

Plan quality varies among planners by level of experience. Several studies showed that the IMRT plans designed by an experienced center are clinically better than those designed by a center with less IMRT experience.[4–6] Moreover, planners lack formal means to evaluate the DVHs of the OARs upon completion of a new plan, other than the Radiation Therapy Oncology Group (RTOG) sparing goals. While these RTOG sparing goals are useful guidelines, they are based on the general population. The RTOG sparing goals thus ignore the specific geometric information of individual patients with regard to the trade-offs between target coverage and normal tissue sparing. Due to patients' geometric variations, the guidelines are not meaningful in cases where the goals are not achievable or can be surpassed.

These unsatisfactory situations call for a method of quality control for the DVHs of the OARs that does not entirely rely on personal judgment, but takes into consideration the geometric variations between patients. To meet this need, this paper proposes a method of quality control that assists planners in identifying potential dose reductions for the OARs at the conclusion of a new plan. It is achieved by comparing the geometric relationships between the OARs and targets of a new patient with the geometric relationships of prior patients, whose plans are maintained in a database. The database serves as an external reference for evaluating the DVHs of the OARs in the new plan. By comparing the geometric configurations, planners can identify related prior patients. The treatment plans of these related prior patients are then retrieved from the database, and used to guide planners in determining whether lower doses to the OARs in the new plan are feasible.

II. METHODS AND MATERIALS

The key challenge of our quality control method is to define a descriptor that not only captures the geometric relationships between the OARs and targets, but also is well-suited for treatment plan retrieval. Given consistent target coverage across patients, the relative spatial configuration of an OAR with respect to a target determines, to a large extent, the dose distribution of the OAR: OARs distant from the target are easy to spare, while proximal or overlapping OARs are difficult.[7] Several head-and-neck studies have used the overlap volume between an OAR and a target as a descriptor of the relative spatial configuration.[8–11] However, the overlap volume is not meaningful when the OAR and target do not overlap. Moreover, it oversimplifies the relative spatial configuration to a single number. To address this challenge, we introduce a general, sophisticated, and robust shape relationship descriptor, the overlap volume histogram (OVH). The OVH is a one-dimensional function associated with an OAR, measuring its proximity to a target. It provides a way to infer the likely DVH of an OAR by allowing comparisons of the relative spatial configurations between patients.

II.A. Definition of the OVH

The OVH describes the fractional volume of the structure of an OAR that is within a specified distance of a target. Given target T and organ O, the OVH is a one-dimensional function giving the percent volume of O that is within a specific distance of r from T

$$\mathrm{OVH}(r) = \frac{|\{p \in O | d(p,T) \leq r\}|}{|O|}, \tag{1}$$

where $d(p,T)$ is the signed distance[12] between point p and target's boundary (negative inside the boundary and positive outside), and the symbol $|\ |$ represents the volume of an object. More simply put, the value of the OVH represents the percentage of the OAR's volume that overlaps with a uniformly expanded or contracted target.

The calculation of the OVH can be thought of as two steps—Uniform expansion and contraction of the target: (1) Target expansion: We first uniformly expand the target with a distance of a mm in all directions. The overlap volume between the expanded target and OAR is then calculated. The expansion with a mm is repeated until the expanded target fully encompasses the OAR, in which situation the overlap volume is the volume of the OAR. Calculation of the overlap volume between the expanded target and OAR is also repeated after each expansion. (2) Target contraction: The target is uniformly contracted with a distance of a mm in all directions. Such contraction is repeated until there is no overlap between the contracted target and OAR. During each a mm contraction, the overlap volume between the contracted target and OAR is calculated. The curve resulting from the target expansion and contraction is the OVH that characterizes the relative spatial configuration of the two objects.

II.B. A simplified example demonstrating the properties of the OVH

Figure 1 illustrates an example of the OVH. Figure 1(a) shows the 3D shapes of two OARs and one target. The target

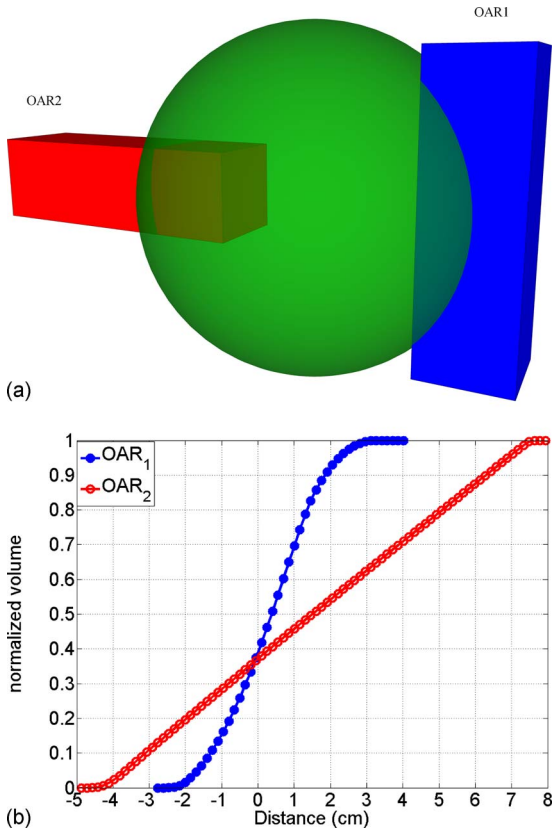

FIG. 1. An OVH example. (a) 3D shapes of the target and OARs. (b) OVHs.

is a sphere with a radius of 7 cm. The OARs are two boxes that are of equal size ($3.7\times3.7\times12.1$ cm^3) but with different spatial relationships with the target. The OVH curves of the two OARs relative to the target are illustrated in Fig. 1(b). By utilizing target contraction, the OVH curves show that OAR_2 is much deeper inside the target than OAR_1; the lengths of OAR_1 and OAR_2 inside the target are 2.2 and 4.4 cm, respectively. In addition, the slope of the OVH curve tells us how fast the target will cover the OAR. For example, for covering 70% volume of OAR_1, the target needs to expand 1.1 cm; for covering the same percent volume of OAR_2, the target needs to expand 3.9 cm. Therefore, by utilizing target expansion and contraction, the OVH quantitatively defines the distance between the OAR and target, and it does not care whether the OAR and the target overlap or not. Moreover, Fig. 1(b) shows that the volumes of the two OARs within the target are roughly the same: OVH(0) =38%. Notably, the previously proposed metric of the overlap volume[8–11] is a single point in the OVH curve, located at the zero crossing.

This example offers a simplified demonstration of the relationship between the OVH and potential to achieve dosimetric sparing of the OARs. The OVH curves show that the nonoverlapping portion of OAR_2 ($r>0$) is more slowly encompassed by the expanded target, in comparison with the nonoverlapping portion of OAR_1. Accordingly, the nonoverlapping portion of OAR_2 is more easily spared than that of OAR_1. However, the OVH curve of OAR_1 is much steeper when $r<0$. This indicates that the overlapping portion of OAR_1 is more easily spared than that of OAR_2.

II.C. Relationship between the OVH and DVH

In a conformal dose distribution, the DVH of an OAR is directly related to the OVH of that OAR. A conformal dose distribution is defined by the following properties: (1) The target's boundary is covered by the isodose surface of prescription dose D_p; (2) any isodose surface is an expansion or contraction of the target's boundary; and (3) isodose distributions are characterized by sharp dose gradients between the OARs and target. In this dose distribution, the larger the expansion distance r_v [at percent volume v, i.e., $\mathrm{OVH}(r_v)=v$] is, the lower the D_v is. The D_v represents the DVH dose at percent volume v, i.e., $\mathrm{DVH}(D_v)=v$. This property makes it possible to compare the DVHs of two OARs (OAR_1 and OAR_2) based on their OVHs

$$r_{v,1}\geq r_{v,2}\Rightarrow D_{v,1}\leq D_{v,2}. \tag{2}$$

For example, applying relation (2) to the OVH curves in Fig. 1(b) leads to the following conclusions: For $v>\mathrm{OVH}(0)$, we have $r_{v,2}>r_{v,1}$; then $D_{v,2}<D_{v,1}$ is expected. For $v<\mathrm{OVH}(0)$, we have $r_{v,1}>r_{v,2}$; then $D_{v,1}<D_{v,2}$ is expected. For $v=\mathrm{OVH}(0)$, we have $r_{v,1}=r_{v,2}$; then $D_{v,1}=D_{v,2}$ is expected.

A conformal dose distribution is not practically achievable due to the irregular shape of targets, the need to spare the OARs, the inhomogeneous densities of patient tissues, and beam arrangements. Nonetheless, relation (2) can still be used to relate the OVH and DVH in cases other than conformal dose distribution: (1) In IMRT planning, planners spend a great deal of effort in making the prescription dose conformal to the target: Ring structures are explicitly created for this purpose; (2) in most cases, the target's DVH dose at 95% volume D_{95} must be larger than prescription dose D_p: $D_{95}>D_p$; (3) the densities of the target and its surrounding soft tissues are often similar. As a result, relation (2) is generally applicable in practical IMRT planning, which usually presents approximately conformal dose distribution around the target. Although this approximation breaks down at large distances, OARs that are far from the target are very easy to spare.

The discussion below presents a head-and-neck example to illustrate the relationship between the OVH and DVH described by relation (2).

II.D. A head-and-neck example illustrating the relationship between the OVH and DVH

Patients with head-and-neck cancer are generally treated by simultaneous integrated boost (SIB),[13] which simultaneously delivers multiple different prescription doses to the electively irradiated nodal regions and the gross disease sites. One of our head-and-neck treatment protocols is to deliver three prescription doses to three PTVs, designated as $PTV^{58.1}$, PTV^{63}, and PTV^{70} with the superscripts representing low, medium, and high prescription dose levels. Accord-

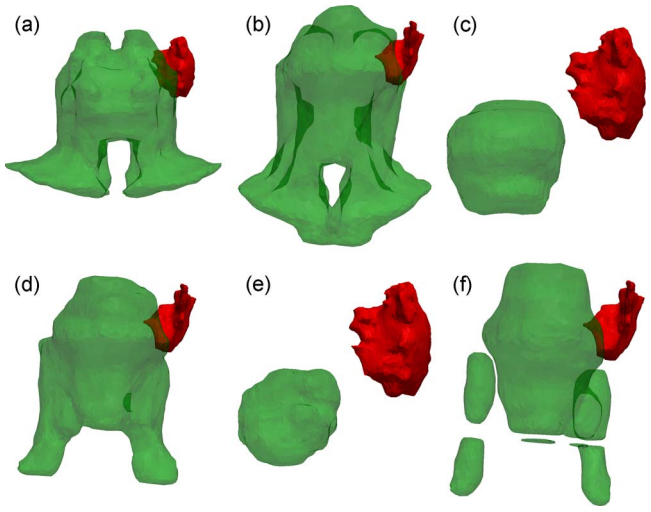

FIG. 2. 3D geometric relationships of left parotids of two patients with respect to the three PTVs of each patient. (a) Patient 1: Left parotid and $PTV^{58.1}$. (b) Patient 5: Left parotid and $PTV^{58.1}$. (c) Patient 1: Left parotid and PTV^{63}. (d) Patient 5: Left parotid and PTV^{63}. (e) Patient 1: Left parotid and PTV^{70}. (f) Patient 5: Left parotid and PTV^{70}.

ingly, each OAR has three OVHs: $OVH^{58.1}$, OVH^{63}, and OVH^{70}, corresponding to each of the three PTVs.

Figure 2 shows the 3D geometric relationships of the left parotids of two patients with respect to their three PTVs. The prescription doses to the three PTVs are 58.1, 63, and 70 Gy, respectively. In the following discussion, we use integers to identify patients in our patient database. Figures 2(a), 2(c), and 2(e) are for patient 1; Figs. 2(b), 2(d), and 2(f) are for patient 5. The OVH curves depicting the geometric relationships of the two parotids with respect to their three PTVs are shown in Fig. 3(a). The OVH curves illustrate that the distances between the left parotid of patient 1 (1 L) and its three PTVs are larger than the distances between the left parotid of patient 5 (5 L) and its three PTVs: $r^{58.1}_{v,1\ \mathrm{L}} > r^{58.1}_{v,5\ \mathrm{L}}$, $r^{63}_{v,1\ \mathrm{L}} > r^{63}_{v,5\ \mathrm{L}}$, and $r^{70}_{v,1\ \mathrm{L}} > r^{70}_{v,5\ \mathrm{L}}$ for any percent volume v. This exactly reflects the geometric relationships shown in Fig. 2. For example, Figs. 2(e) and 2(f) show that 5 L is closer to its PTV^{70} than 1 L is to its PTV^{70}. Figure 3(a) similarly indicates that 5 L is closer to its PTV^{70} since the OVH^{70} curve of 5 L is on the left of the OVH^{70} curve of 1 L: $r^{70}_{v,1\ \mathrm{L}} > r^{70}_{v,5\ \mathrm{L}}$ for any v.

Applying relation (2) would lead to the conclusion that 1 L should receive a lower dose than 5 L: $D_{v,1\ \mathrm{L}} < D_{v,5\ \mathrm{L}}$ for any v. However, the actual DVH curves of the two parotids in Fig. 3(b) show the opposite. This discrepancy indicates that the dose of 1 L can be further reduced at least below $D_{v,5\ \mathrm{L}}$. Further sparing of 1 L should thus be possible. The replanning results of patient 1 are detailed in Sec. III A.

II.E. A quality control method for evaluating the DVHs of the OARs

As discussed in Sec. II C, relation (2) offers a way to evaluate the DVHs of the OARs in IMRT planning. Specifically, if $r_{v,1} \geq r_{v,2}$ for a certain range of v, then $D_{v,1} \leq D_{v,2}$ is expected in this range. In the context of quality control,

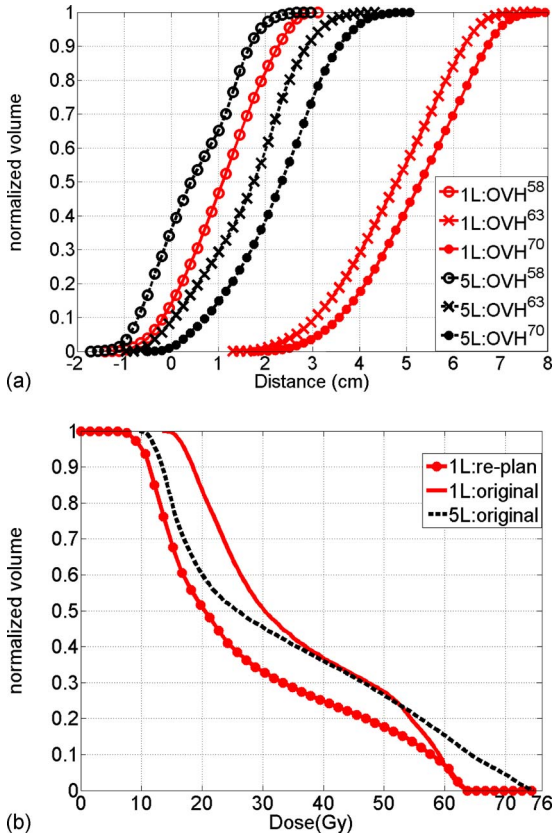

FIG. 3. OVHs and DVHs of the left parotids of patients 1 and 5 (1 L and 5 L). (a) OVHs of 1 L and 5 L. (b) DVHs of 1 L and 5 L.

when $r_{v,1} \geq r_{v,2}$ for a certain range of v, if we have $D_{v,1} > D_{v,2}$ for some v in this range, then the value of $D_{v,1}$ should be reduced at least to $D_{v,2}$ so as to satisfy $D_{v,1} \leq D_{v,2}$. Further sparing of OAR_1 is possible. This is the basic rationale behind our quality control method. Based on the above discussion, the quality control method proceeds as follows:

(1) The data of prior patients with the same disease site and treatment protocol are collected. For each patient, the database stores the DVHs of the OARs, the DVHs of the targets, and the OVHs of the OARs.
(2) At the conclusion of a new plan, the DVH and the OVH of an OAR q are used to query the database. The query returns the set $\{i\}$ of prior plans that satisfy the following conditions for the percent volume v of that OAR's RTOG sparing goal:

$$\{i: r_{v,q} \geq r_{v,i} \quad \text{and} \quad D_{v,q} \geq D_{v,i}\}. \tag{3}$$

(3) If some stored plans meeting both conditions of set (3) are identified, it may be possible to deliver a lower dose, $\min_{\mathrm{set}(3)}\{D_{v,i}\}$, to the query OAR. Further planning may be necessary to reduce the dose of the query OAR.

II.F. Experimental demonstration of the quality control method: A head-and-neck retrospective study

To verify the effectiveness of our method for quality control, we have conducted a preliminary retrospective study of

head-and-neck patients. For this study, we constructed an anonymized database of 32 head-and-neck patients who underwent IMRT with nine coplanar 6 MV fixed photon beams from year 2007 to 2008. The treatment protocols for these 32 patients are the same: Each patient has three PTVs: $PTV^{58.1}$, PTV^{63}, and PTV^{70}. The IMRT treatment planning software that our institution used for the head-and-neck was PINNACLE[3]. The database contained the geometric files and DVH values for the three PTVs and 13 OARs (brain, brainstem, cord+4 mm, oral mucosa, left parotid, right parotid, left inner ear, right inner ear, larynx for edema, esophagus, left brachial plexus, right brachial plexus, and mandible) of each patient. Since each patient has three PTVs, we computed three OVH curves ($OVH^{58.1}$, OVH^{63}, and OVH^{70}) for each patient's OAR, and stored them in the database.

To account for the three PTVs in head-and-neck cases, the quality control method developed in Sec. II E has to be modified. Specifically, set (3) in Sec. II E should be modified in the following way: The query is to find the set of the stored plans $\{i\}$ satisfying

$$\{i: r_{v,q}^{58.1} \geq r_{v,i}^{58.1},\ r_{v,q}^{63} \geq r_{v,i}^{63},\quad \text{and} \quad r_{v,q}^{70} \geq r_{v,i}^{70},\quad \text{and}\quad D_{v,q} \geq D_{v,i}\}. \tag{4}$$

Then, $\min_{\mathrm{Set}(4)}\{D_{v,i}\}$ is selected as the expected dose for the query OAR. Percent volume v is OAR-specific and determined by the RTOG head-and-neck protocols.[14]

We applied our method to the evaluation of parotid DVHs. Parotids produce a major part of the salivary secretions. The most prevalent side effect of radiation in head-and-neck patients is xerostomia, which is cited by patients as the major cause of decreased quality of life.[15–17] In the RTOG head-and-neck protocols, the dosimetric sparing goal for parotids is (1) the mean dose to either parotid is less than 26 Gy; (2) at least the 50% volume of either parotid receive less than 30 Gy: $V(30\ \mathrm{Gy}) < 50\%$; or (3) at least 20 cc of the combined volume of both parotids receive less than 20 Gy. Our institution uses $V(30\ \mathrm{Gy}) < 50\%$ as the sparing goal. As a result, $v = 50\%$ was chosen for set (4).

In our experimental demonstration, each parotid in the database was queried against the other 63 parotids to determine whether a lower dose to the query parotid was to be expected. If a lower dose to the query parotid was determined to be expected, that parotid was flagged.

To confirm the quality control mechanism of our method, replanning of both flagged and unflagged parotids was carried out. The criteria that we followed for replanning were as follows:

(1) DVH constraints in the original plans were used as baselines for replanning. Beam arrangements in replanning were the same as the original plans.
(2) Dose reduction was applied to both the flagged and unflagged parotids. For the flagged parotids, a DVH objective $D_{50} = \min_{\mathrm{Set}(4)}\{D_{50,i}\} - D$ was used. For the unflagged parotids, a DVH objective $D_{50} = D_{50,q} - D$ was used, where $D_{50,q}$ is the original dose of the query parotid. Here, D is introduced to determine (1) whether the doses to the flagged parotids can be further reduced below the expected doses and (2) whether the doses to the unflagged parotids can be further reduced. In replanning, we set the weights (penalties) of parotids at the same values as the weights of the PTVs.
(3) The DVH curves of the three PTVs were the same as the original plans or the D_{95} of the three PTVs was the same or higher than the original plans.
(4) For the brainstem, cord+4 mm, brain, esophagus, brachial plexus, and mandible, the maximum doses were not allowed to exceed those of the original plans.
(5) The mean doses of the inner ear and oral mucosa were not allowed to exceed those of the original plans.
(6) $V(50\ \mathrm{Gy})$ of the larynx for edema was not allowed to exceed that of the original plans.

III. RESULTS AND DISCUSSION

Utilizing the modified quality control method [see set (4) in Sec. II F] discussed above, we found that parotids (left parotid, right parotid, or both) of 21 patients among the 32 prior patients could receive lower doses than they actually did. The 17 parotids that promised the greatest reduction in D_{50} were flagged. These 17 parotids came from 13 patients. Additionally, our method indicated that the doses of the other nine parotids of these 13 patients were not expected to be reduced, so they were included in the replanning process as controls. Replanning with an effort to reduce D_{50} was conducted on these 26 parotids. In replanning, we followed the replanning criteria discussed in Sec. II F.

PTV coverage and OAR sparing were compared between the 13 original and replans at selected relevant dose/volume points by using the pairwise Wilcoxon p test. The statistical significance is $p < 0.05$. The comparisons are illustrated in Table I. It shows that sparing of parotids is significantly better ($p = 0.0172$) in the 13 replans: Averages of $V(30\ \mathrm{Gy})$ for the original and replans are 55% and 49%, respectively. It also shows that replanning compromised neither PTV coverage nor OAR sparing. The reason for the low $PTV^{58.1}$ coverage (D_{95}) shown in Table I is that parts of the $PTV^{58.1}$ are outside some of the patients' skin. Our institution uses 5 mm expansion margin for the PTVs. For some patients, the $PTV^{58.1}$ is so large that parts of the $PTV^{58.1}$ are in the air. In calculating the OVH, we used the whole PTV as the target. To be consistent, the DVHs of the whole PTVs were stored in our database and used in the query.

III.A. An example of query and replanning results of a patient

Table II shows the query results of the left parotid of patient 1 (1 L). The original D_{50} of 1 L was 30.3 Gy. Through a database search, the expected D_{50} of 1 L was determined to be 25.8 Gy, which corresponds to the D_{50} of 5 L (see Sec. II D for the geometric information regarding 1 L and 5 L). 23 Gy, corresponding to the right parotid of patient 24 (24 R), was not selected as the expected dose for 1 L since the $PTV^{58.1}$ coverage of patient 24 is low. The query

TABLE I. p values and averages of the selected relevant dose/volume points for the original and replan results.

PTVs	Evaluation point (Gy)	Average	p [a]
$PTV^{58.1}$	D_{95}	55.6:55.9[b]	0.977
PTV^{63}	D_{95}	64.3:64.3	0.665
PTV^{70}	D_{95}	69.9:69.9	0.998
	D_5	73.5:73.7	0.4025
OARs	Evaluation point (Gy)	Average	p [a]
Brain	$D_{1\ cc}$	50.4:45.3	0.2934
Oral mucosa	Mean dose	50.1:48.2	0.5834
Cord+4 mm	$D_{0.1\ cc}$	43.4:41.5	0.1891
Esophagus	$D_{1\ cc}$	56.7:53	0.2366
Larynx for edema	$V(50)$ (%)	48.6:41.5	0.6438
Brainstem	$D_{0.1\ cc}$	51.5:45.5	0.000731
Mandible	$D_{0.1\ cc}$	70.7:70.1	0.8399
Brachial plexus	$D_{0.1\ cc}$	61.7:60.4	0.0915
Inner ear	Mean dose	34.6:28.8	0.0814
Parotid	$V(30)$ (%)	55:49	0.0172

[a]The statistical significance is $p<0.05$.
[b]Averages of D_{95} of the $PTV^{58.1}$ is low because parts of the $PTV^{58.1}$ are outside some patients' skin.

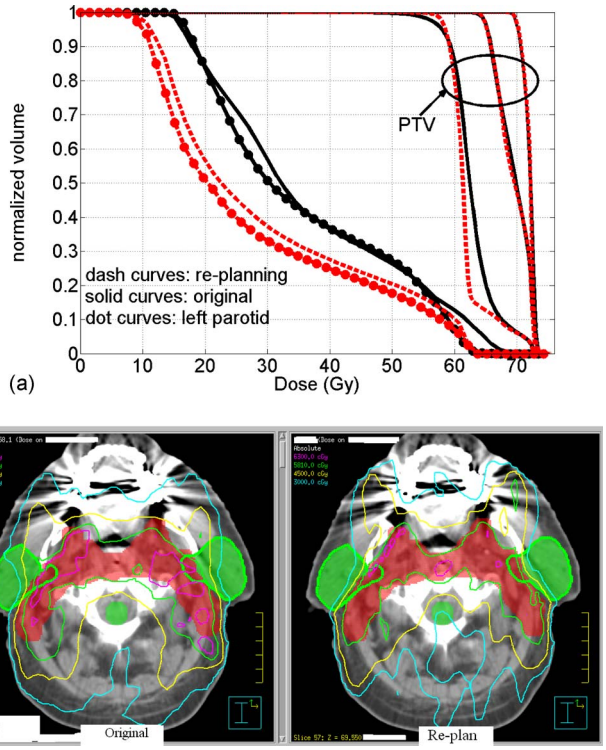

FIG. 4. Original and replanning results of patient 1. (a) DVHs of parotids and PTVs. (b) Isodose lines.

results indicate that the D_{50} of 1 L could potentially be reduced to at least 25.8 Gy. Another query was done with the right parotid of patient 1 (1 R) and found that the D_{50} of 1 R could potentially be reduced from 32 Gy to at least 25 Gy.

Figure 4(a) illustrates the replanning results of the DVHs of both parotids and the three PTVs of patient 1. The replanning results for other OARs are illustrated in Table III. The isodose lines of the original and replanning plans are shown in Fig. 4(b). The replanning results indicate that the doses of both of patient 1's parotids are nontrivially reduced without compromising target coverage or other OAR sparing. Indeed, the target coverage for $PTV^{58.1}$ is improved. The details of the replanning results for the 17 flagged and nine unflagged parotids are provided in the following section.

III.B. Replanning results of the 17 flagged and nine unflagged parotids

The replanning results for the 26 parotids in the 13 patients demonstrate that our quality control method accurately identified both the parotids that benefited from additional planning and those for which additional planning provided marginal benefits. The D_{50} results of the 17 flagged and nine unflagged parotids are shown in Figs. 5(a) and 5(b), respectively. For comparison, the expected D_{50} as determined by database search $\min_{\mathrm{Set}(4)}\{D_{50,i}\}$ is also shown in Figs. 5(a) and 5(b). For the nine unflagged parotids, the expected D_{50}

TABLE II. Query results of the left parotid of patient 1(1 L).

	D_{50} (Gy)	$r_{50}^{58.1}$ (cm)	r_{50}^{63} (cm)	r_{50}^{70} (cm)	$PTV^{58.1}$ [a] (Gy)	PTV^{63} [a] (Gy)	PTV^{70a} (Gy)
1: L parotid[b]	30.3	1.09	4.79	5.29	57.9	65.3	70.1
5: L parotid[c]	25.8	0.42	1.76	2.35	59.3	65.9	69.9
5: R parotid[c]	27.3	0.38	1.55	2.16	59.3	65.9	69.9
3: L parotid[c]	27.6	0.66	1.74	2.28	58.4	65.4	69.1
9: L parotid[c]	28.6	0.25	1.06	2.89	57.8	64.2	69.9
6: R parotid[c]	28	0.39	1.97	3.61	55.9	64.1	69.7
12: L parotid[c]	27.4	0.31	2.11	2.18	54.3	66.3	69
14: R parotid[c]	28.5	−0.11	3.43	3.54	50	65.6	70.1
24: R parotid[c]	23	0.32	2.43	4.53	46.6	63.9	71.1

[a]DVH dose at 95% volume of the PTV: D_{95}. D_{95} of the $PTV^{58.1}$ of some patients is low because parts of the $PTV^{58.1}$ are outside the patients' skin.
[b]Query parotid.
[c]Query results.

TABLE III. Replanning results of the OARs of patient 1.

Patient 1	Brain: $D_{1\ cc}$ (Gy)	Brainstem: $D_{0.1\ cc}$ (Gy)	Cord+4 mm: $D_{0.1\ cc}$ (Gy)	Esophagus: $D_{1\ cc}$ (Gy)	Oral mucosa[a] (Gy)	L inner ear[a] (Gy)	R inner ear[a] (Gy)	Mandible: $D_{0.1\ cc}$ (Gy)	Larynx for edema[b] (%)
original	57.4	51.2	39.7	57.1	48.3	57.2	40.6	63.6	61
replan	51.7	44.7	35.9	53.3	47.2	43.7	30.4	61.9	59

[a]Mean dose.
[b]$V(50\ Gy)$.

are the same as the original. After replanning, the average reductions in D_{50} for the 17 flagged parotids were 6.6 Gy. In contrast, the average reductions in D_{50} for the nine unflagged parotids were only 1.9 Gy. Figures 5(c) and 5(d) show $V(30\ Gy)$ of the replanning results of the 17 flagged and nine unflagged parotids, respectively. Originally, 11 of these 17 flagged parotids did not meet the RTOG sparing goal of $V(30\ Gy) < 50\%$. Replanning reduced them to three.

For parotid queries, our quality control method uses D_{50} instead of $V(30\ Gy)$. $V(30\ Gy)$ is not used due to the relationship between the OVH and DVH as described by relation (2). In other words, this quality control method is an indirect way of minimizing $V(30\ Gy)$ of the query parotids. In most cases, reduction in D_{50} results in a reduction in $V(30\ Gy)$.

III.C. Discussion

The goal of our quality control is to help planners or physicians to decide whether further sparing of the OARs is possible without compromising PTV coverage or other organ sparing. However, once trade-offs required to achieve the RTOG sparing goal of an OAR are achieved, it is not clear, from a clinical standpoint, whether further sparing of the OAR will translate into a better clinical outcome. Although this is an important clinical problem, it is beyond the scope of the paper.

Patient's clinical information is also a major consideration in treatment planning. Physicians or planners should always combine our method with patient's clinical information to

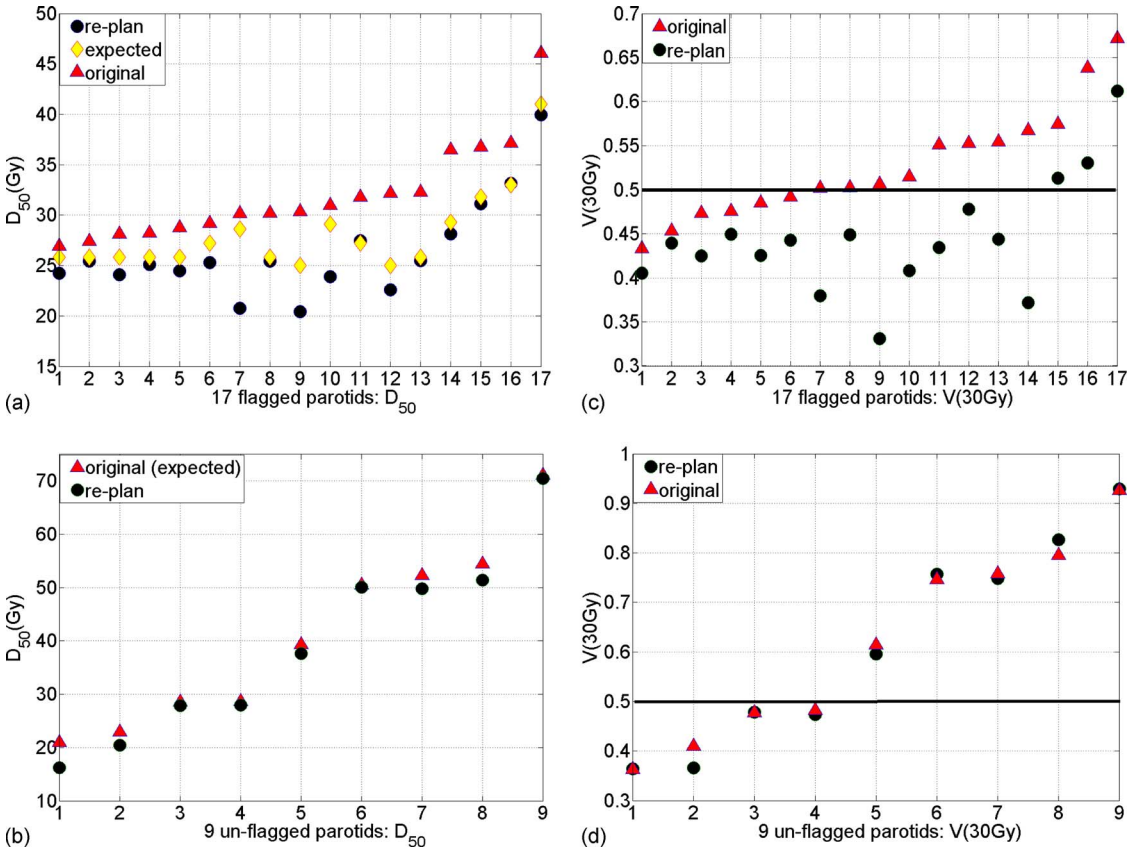

FIG. 5. Replanning results of 26 parotids of the 13 patients. (a) 17 flagged parotids: D_{50}. (b) Nine unflagged parotids: D_{50}. (c) 17 flagged parotids: $V(30\ Gy)$. (d) Nine unflagged parotids: $V(30\ Gy)$.

decide whether further sparing of OARs is needed. Generally speaking, the treatment protocol applied to a patient has reflected the clinical information of that patient. The selection of certain treatment protocol has taken into account the patient's conditions that are clinically significant. As a result, patients with the same treatment protocol normally have similar clinical conditions. To consider patient's clinical information, the reference database should be tailored to specific disease sites and treatment protocols. For example, all the 32 head-and-neck patients in our reference database have the same treatment protocol: Simultaneously (IMRT-SIB technique) deliver three prescription doses of 58.1, 63, and 70 Gy to the three PTVs, respectively. This reference database is thus only good for the quality control of the head-and-neck patients with that treatment protocol. For different disease sites and treatment protocols, a corresponding reference database is needed. In addition, the reference database is built upon prior clinically approved treatment plans that reflect the clinical trade-offs that were made for prior patients. Although the database inherently includes prior physicians' decisions on such clinical trade-offs, there remain cases in which patients' clinical conditions require special attention. These conditions are generally known ahead of planning, so physicians and planners may exercise their discretion in combining our method with those special conditions. Furthermore, recognizing that our database as currently proposed does not adequately consider those special cases; further studies should strive to improve in this regard. Nevertheless, the retrospective study has demonstrated that our method produces promising results. It serves as a sound starting point to experiment quality control quantitatively.

Adoption of our method will provide better treatment plan consistency. We understand that a model is needed to ensure that the database improves in quality over time. By making a goal that the quality of each new plan must exceed the plan quality of past plans in the database, we can have the quality of the database improve over time in a systematic way. We are exploring models for database learning in this way. The current study gives us a basis to begin to systematically and continually improve treatment plan quality in our practice. An area of future research in this regard is to compare and share patient databases across multiple institutions.

Generalization of our quality control method to other OARs and disease sites requires further investigation. It should be noted that our method is based on the OAR-PTV relationship characterized by the OVH. Given consistent target coverage across patients, our method assumes that the dose distribution of an OAR is exclusively determined by the distance between that OAR and targets. However, other geometric factors, such as the relative spatial relationship of that OAR to its nearby OARs (OAR-OARs relationship), also play the roles in deciding the dose distribution of that OAR. Incorporating those factors into our quality control method is currently hampered by the lack of a geometric descriptor characterizing this OAR-OARs relationship, the limited database size and combinatorial explosion in dimensionality. In this paper, we used parotids of head-and-neck patients as a demonstration for our OVH-based quality control. IMRT plans for the head-and-neck are demanding since there are over 13 OARs and multiple PTVs that need to be considered. Additionally, parotids often overlap with PTVs, which makes planning more complicated. In light of the complexity of head-and-neck planning, the promising results of the method demonstrate that this OAR-PTV approximation is applicable for parotids. Whether this OVH-based quality control method is applicable to other disease sites and OARs requires further investigation.

IV. CONCLUSIONS

IMRT treatment plan quality relies on the experience of and the time available to the planner. An effective quality control mechanism for evaluating the DVHs of the OARs is highly desirable. To address this need, we proposed a method that planners can use to evaluate the DVHs of the OARs in a new plan. This method contains two major components: (1) The overlap volume histogram, a shape relationship descriptor characterizing the relative spatial configuration of an OAR with respect to a target; and (2) a database of prior patients serving as an external reference. At the conclusion of a new plan, planners run an OVH-guided search through the database which identifies related patients; the new plan's DVH of the OAR is evaluated against the search results, and the amount of expected dose reduction is reported. To illustrate the operation and effectiveness of our method, we presented an application of it to the parotids for head-and-neck patients. This example demonstrates that the method effectively identifies parotids which benefit from further dose reductions and those where satisfactory doses have been achieved. Adoption of such a method will advance the quality of current IMRT planning, providing better treatment plan consistency.

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